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Quench Development in Coated Conductors

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Coated Conductor에서의 퀜치 거동

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Abstract

We measured and analyzed the quench development in coated conductor (CC) tapes. The CC was grown on hastelloy substrates and has an Ag protection layer. The tapes were subjected to simulated AC fault currents for quench development measurement. They were immersed in liquid nitrogen during the experiment. The quench resistance increased rapidly first, and the increase slowed down afterwards. It increased linearly with applied voltage at lower voltages, and depended less strongly on applied voltage at higher voltages. The resistance was compared with that of Au/YBCO films grown on sapphire substrates, and found to increase more monotonously than the latter. Data were analyzed quantitatively with the concept of heat transfer within the tape and the surrounding liquid nitrogen. A heat balance equation was derived and solved, taking into consideration temperature dependence of thermal parameters of the tapes. Solutions, together with values of thermal parameters taken from the literature, explained the data well. Cooling by liquid nitrogen affected the quench development considerably at lower applied voltages. Dependence on applied voltages could be also understood quantitatively.

Keywords : quench, coated conductor, heat transfer, voltage dependence

I. Introduction

The coated conductor (CC) is an attractive material for superconducting power devices, particularly for superconducting fault current limiter (SFCL). It can transform into the normal-conducting state in milliseconds, have high resistance in that state, and return to the superconducting state once the faults are released. The SFCL is a protection device that limits the fault current in electric power systems using properties of superconductors. The SFCL limits the fault current before it reaches the first peak. It thereby enables one to use circuit breakers of lower capacity, and enhances power system reliability. For this reason there has been active research going on

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SFCLs [1-4].

Knowledge on quench properties of the material is important for the research and development of SFCLs, because quench property determines their performance. However, there has not been much work done on the quench properties of coated conductors. In particular, deep understanding of quench based on basic properties of materials has not been done yet.

In this work, we measured and analyzed quench development in CC grown on hastelloy substrates. Quench resistance data were interpreted in terms of heat transfer within the CC tape and to the surrounding liquid nitrogen. In analysis, temperature dependence of thermal parameters was taken into consideration.

II. Experimental details

The CC tape samples used in the experiment were purchased from SuperPower Inc. The YBCO layer was coated on a 50 μm thick hastelloy C 276 substrate, and had a 2 μm thick Ag layer. The samples were 1.2 cm and 101 cm long, and had critical current of about 275 A at 77 K in self field with 1 μV/cm criterion.

Quench resistance of the sample during the fault was measured, using a fault simulation circuit (Fig. 1). An AC power supply was used as the voltage source, V_o. The fault was simulated by closing a switch S_1, connected across the load, and cut off with a switch S_2 several cycles after the fault start so that the element would not be subjected to fault currents for unnecessarily long time. Voltages and currents were measured simultaneously with a multi-channel data acquisition system. During the measurement, the sample was immersed flat in liquid nitrogen for effective cooling. Both sides of the sample were in contact with liquid nitrogen.

III. Results and discussion

Fig. 2 shows quench resistance of a CC tape sample after the fault at applied voltage of 50 V.

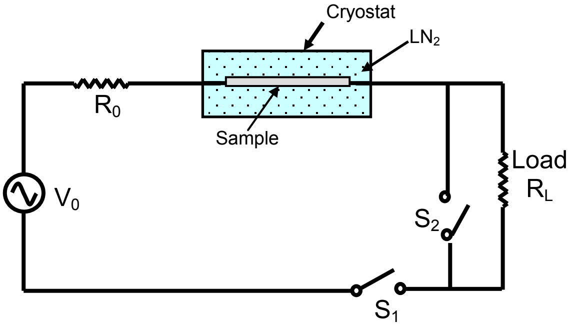

Fig. 1. A schematic diagram of the quench resistance measurement circuit.

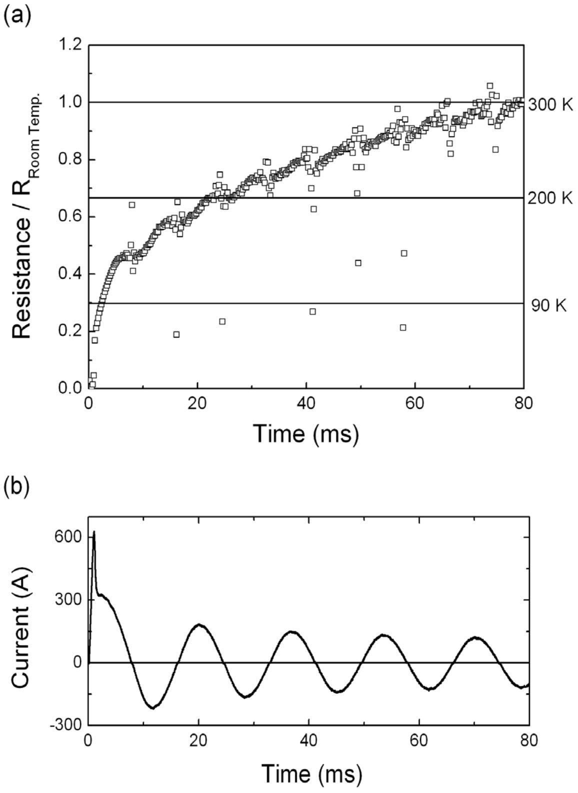

Fig. 2. (a) Resistance of, and (b) current in a coated conductor tape during the fault at applied voltage of 50 V.

The resistance was normalized with the room temperature value, 0.57 Ω. Horizontal lines indicate resistance at selected sample temperature. Temperatures were estimated from the relation between resistance and temperature of the samples in the normal state. The resistance increased rapidly at the very beginning, and then slowly afterwards.

The resistance was measured at various voltages to see the voltage dependence of quench development. The result was shown in Fig. 3. The resistance increased in the similar pattern. The resistance increased rapidly at the very beginning, and then slowly afterwards. Increase rate was higher at higher applied voltages. In order to see voltage depence of quench resistance more clearly, resistance at selected times was plotted as a function of applied volage. The resistance increased linearly with applied voltage at lower applied voltages, and slower at higher voltages.

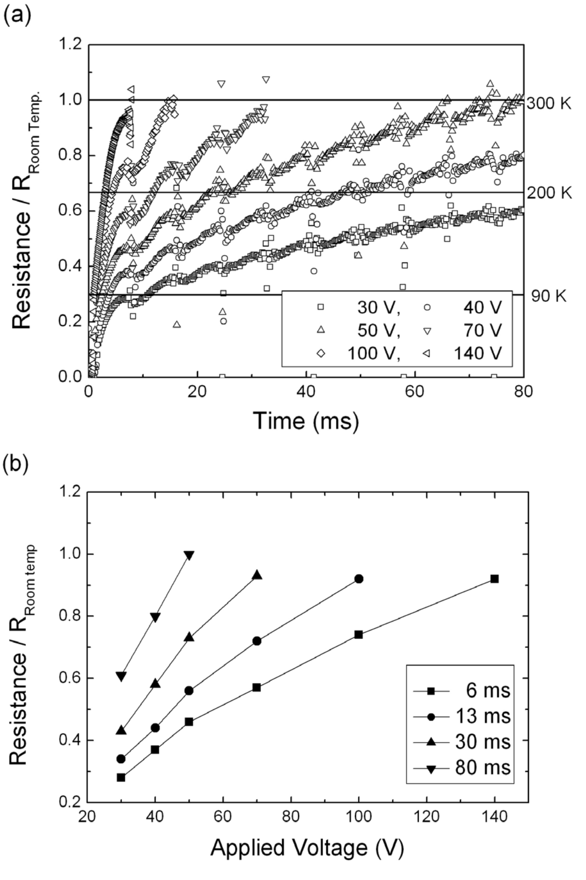

Fig. 3. (a) Resistance of a coated conductor tape after the fault as a function of time at selected applied voltages, and (b) as a function of applied voltage at selected times. Lines between symbols in (b) are for guiding eyes only.

For comparison of quench development in CC tapes with that in Au/YBCO films on sapphire substrates, quench resistance of the films of 2 inch- and 4 inch-diameter was measured. The results are shown in Fig. 4, along with data for a CC tape. At the beginning of the fault, resistance of all samples increased rapidly at the same time. But, it behaved differently afterwards. Resistance of the Au/YBCO film of 2 inch diameter increased fast up to around 26 ms and the increase slowed down. Resistance of the film of 4 inch diameter behaved similarly to that of the CC tape, but slightly different. It increased slightly faster up to about 50 ms, and then slightly slower afterwards. Resistance of the CC tape increased more monotonously with time.

The observed quench behavior of CC tapes could be quantitatively explained in terms of heat transfer within the tape and to the surrounding liquid nitrogen. A part of the heat generated in the tape during

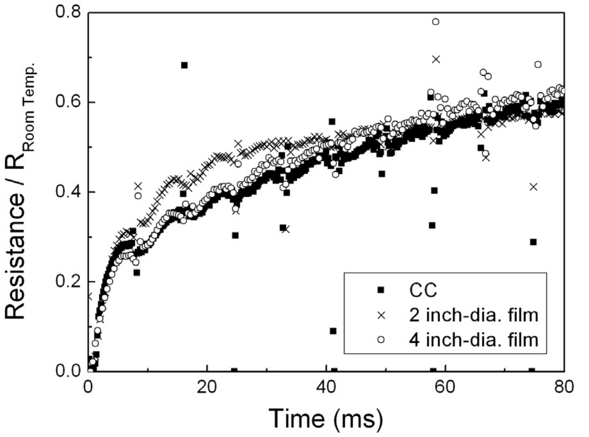

Fig. 4. Resistance of a coated conductor tape, a 2 inch- and a 4 inch-diameter Au/YBCO films on sapphire substrates. Applied voltages are 30 V, 100 V, and 350 V, respectively.

quenches increased their temperature, and the rest was transferred to surroundings. A heat balance equation describes this in a mathematical form [5]:

$$c\frac{\partial T'}{\partial t} + \{\alpha\delta(z) + \alpha'\delta(z+d)\}T' + \nabla \bullet (-\kappa\nabla T') = p, \tag{1}$$
$$\text{where } T' = T - T_b.$$

Here, c, α, α', d, κ, T_b, and p are specific heat, coefficient of heat transfer per unit area from the front and the back sides to surroundings, thickness of the sample, thermal conductivity, heat bath temperature, and density of power dissipated in the tape during quenches, respectively. Terms on the left-hand side describe the heat that increases the sample temperature (the first term), and the heat transferred from the sample to surroundings and neighboring parts (the second and the third terms).

For the circuit drawn in Fig. 1, the integration of the right hand side of Eq. (1) is expressed as $\int p dv = \int \frac{E^2}{\rho} dv = \frac{R}{(R+R_0)^2} V_0^2$, where R is the quench resistance of the whole CC tape. V_0 and R_0 are defined in Fig. 1. Most of the heat is thought to have been generated in the Ag layer because of low electrical resistivity of Ag, despite its thin thickness. Since the substrate is relatively thin, its temperature is though to have been fairly uniform and similar to that of the Ag layer, except at the beginning of the quench. Integrating Eq. (1) over the volume of the tape then leads to:

$$C\frac{\partial T'}{\partial t} + GT' = \frac{R}{(R+R_0)^2} V_0^2 \tag{2}$$

Here, C is heat capacity of the tape, and $G \equiv S(\alpha + \alpha')$, where S is the surface area of the tape. Dividing Eq. (2) by C becomes:

$$\frac{\partial T'}{\partial t} + \frac{\alpha + \alpha'}{cd} T' = \frac{R}{C(R+R_0)^2} V_0^2 \tag{3}$$

According to the literature, the thermal parameters c and α depend on temperature, particularly at lower temperatures [5, 6]. Specific heat data for Ni was used as the substitute for data for hastelloy, since the latter was available only for temperatures higher than 800 K (Fig. 5). Hastelloy C 276 is composed of Ni (~ 57 %), Cr (~15 %), Mo (~16 %), Fe (~6 %), and W (~4 %). Specific heat of Ni increases more or less linearly with temperature at temperatures around the liquid nitrogen temperature, T_b, and the increase slows down at around 70 K above T_b (Fig. 5). The heat transfer coefficient decreases slightly with temperature. The ratio of specific heat to heat transfer coefficient, c/α, was approximated to be proportional to T' for simplicity: that is, $c/\alpha \approx h\,T'$, where $h \approx 1.9$ s/(cm·K). Substituting these relations into Eq. (3) leads to:

$$\begin{aligned}\frac{\partial T'}{\partial t} + \frac{1}{h^{'}d} &= \frac{RV_0^2}{C(R+R_0)^2} \\ &\approx \frac{V_0^2}{C(R+2R_0)} \text{ for } R > R_0\end{aligned}, \tag{4}$$

where $h' \equiv c/(\alpha'+\alpha)/T'$.

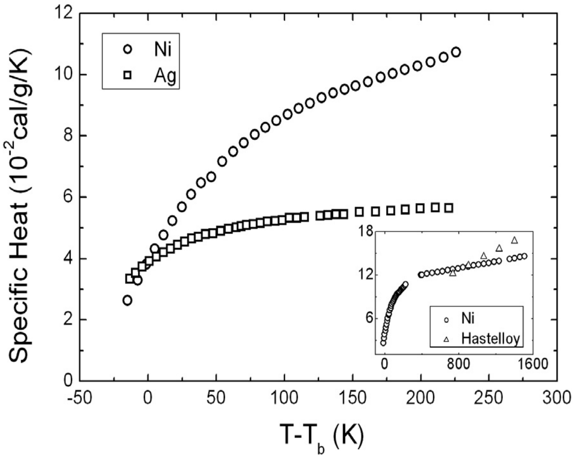

Fig. 5. Temperature dependence of specific heat for Ni and Ag [6]. The inset shows the dependence for Ni and hastelloy C.

After the quench is completed and the whole CC tape turns into the normal-conducting state, resistance of the tape increases because its temperature increases. In the normal-conducting state, resistance increases linearly with temperature. In other words, $R = a\,T + b = a\,T' + \beta$, where a, b, and β are constants. Heat capacity of the CC tape is the summation of heat capacity of the components that the tape is composed of. That is, $C = S\,(c_{\text{substrate}}\,d_{\text{substrate}} + c_{\text{buffer}}\,d_{\text{buffer}} + c_{\text{YBCO}}\,d_{\text{YBCO}} + c_{\text{Ag}}\,d_{\text{Ag}})$. Since the thickness of the substrate, $d_{\text{substrate}}$, is much thicker than the rest, and since the specific heat of the components are similar, C can be approximated to be $\approx c_{\text{substrate}}\,d_{\text{substrate}}\,S$. If C is approximated into $g\,T' + q$ for simplicity, Eq. (4) becomes:

$$\frac{\partial T'}{\partial t} + \frac{1}{h'd} \approx \frac{B}{(T'+D)(T'+A)},$$
$$\text{where } B = \frac{V_0^2}{ga},\quad D = \frac{q}{g}, \tag{5}$$
$$\text{and } A = \frac{\beta + 2R_0}{a}.$$

This equation has an analytic solution. Solution to this equation with an initial condition $T'(t_0) = T'_0$ is:

$$-\frac{t-t_0}{hd} = T' - T'_0 + K\left[\ln\frac{G-T'}{G-T'_0} - \ln\frac{H-T'}{H-T'_0}\right],$$
$$\text{where } K = Bh'd \Big/ \sqrt{(D-A)^2 + 4Bh'd},$$
$$G = \left(-(D+A) + \sqrt{(D-A)^2 + 4Bh'd}\right)\Big/2, \text{ and}$$
$$H = \left(-(D+A) - \sqrt{(D-A)^2 + 4Bh'd}\right)\Big/2. \tag{6}$$

If the cooling term, the second term in Eq. (5), is neglected, the solution becomes very simple:

$$B(t-t_0) = \frac{T'^3 - T'^3_0}{3} + (A+D)\frac{T'^2 - T'^2_0}{2} + AD(T' - T'_0) \tag{7}$$

This solution tells that voltage dependence of T' is affected by A and D, which were around 100 K and 200 K in this case, respectively. For $T' < A, D$, T' tends to be proportional to V_0, whereas for $T' > A, D$, T' tends to be proportional to $V_0^{2/3}$. This explains Fig. 3. When the resistance is small, or equivalently, when the temperature is low, it tends to increase linearly with V_0. When the resistance is larger, the dependence on V_0 is less strong.

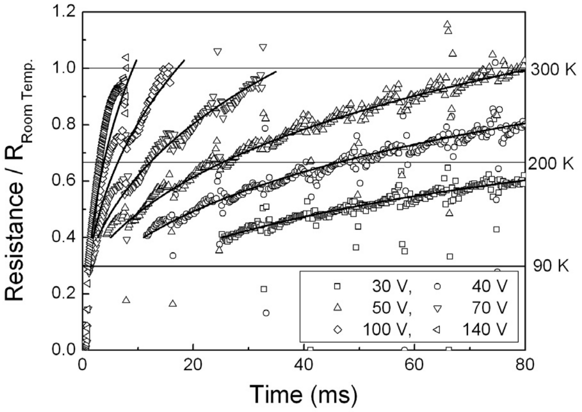

Fig. 6. Calculation result (lines) for resistance of the CC tape after quench completion. Data (symbols) are also shown for comparison.

Time dependence of resistance after quench completion was calculated for the CC tape. In calculation, only V_0 was varied, and values of all other variables were shared. The result is presented in Fig. 6, along with data. Better fit required the cooling term to be included, especially for lower-V_0 data. Since the substrate is fairly thin, cooling by the liquid nitrogen is not expected to be negligible. The calculation agreed well with data. In particular, voltage dependence could be explained quantitatively.

IV. Conclusions

We measured and analyzed the quench development in CC tapes. The quench resistance increased rapidly first, and the increase slowed down afterwards. It increased linearly with applied voltage at lower voltages, and depended less on applied voltage at higher voltages. The resistance was compared with that of Au/YBCO films grown on sapphire substrates, and found to increase more. Data were analyzed quantitatively with the concept of heat transfer within the tape and the surroundings. A heat balance equation was derived, considering temperature dependence of thermal parameters of the tapes. Solutions explained the data well. Cooling by liquid nitrogen was found to have affected the quench development considerably, especially at lower applied voltages. Dependence on applied voltages could be also understood quantitatively. Results of this work will be applied to the design of superconducting fault current limiters based on the CC tapes.

Acknowledgments

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